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ICE PRESSURE AGAINST DAMS: STUDIES OF THE EFFECTS OF TEMPERATURE VARIATIONS

By Bertil LÖfquist

POWER DIVISION

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EXPLANATORY STATEMENT

In recent years a number of changes have been observed in the concepts applied to the design of masonry dams. The work that leads to such changes is being done by different men, different organizations, and often in different countries. Under a Power Division chairman, a Joint Committee on Masonry Dams was formed in 1938, with representatives from the Construction, Irrigation, Power, Soil Mechanics and Foundations, Structural, and Waterways divisions, to make that widespread experience readily available through the medium of the Society's technical publications.

The Subcommittee on Ice Pressure, formed in 1947, has conducted a vigorous search for basic information on the pressure that ice exerts against dams—in Switzerland, Norway, Sweden, and Canada, as well as the United States.

Three papers (*Proceedings-Separate*, Nos. 160, 161, and 162) prepared under the sponsorship of the Subcommittee, are presented to encourage the assembly of facts and figures on this important subject. Each paper is open to discussion, within its scope, independently of the remaining two. When the discussion is closed and the authors' rebuttals have been presented, the group will be collated as a single symposium paper in *Transactions*, from which reprints will be available. With the completion of this work, the Subcommittee recommends that:

- (1) Interested organizations be encouraged to develop their work in connection with ice pressure against dams, and urged to maintain mutual liaison in this field;

- (2) The present Symposium be published by the Society as a statement of the present state of knowledge regarding ice pressure against dams, and as a basis for discussion; and

- (3) The Society, possibly through the Power Division, should reconsider the matter in three or four years' time when the results of further investigations have become generally available.

The *Transactions* printing will include a final report, presented as a "Foreword" to the Symposium.—Ed.

AMERICAN SOCIETY OF CIVIL ENGINEERS

Founded November 5, 1852

PAPERS

ICE PRESSURE AGAINST DAMS:
STUDIES OF THE EFFECTS OF TEMPERATURE
VARIATIONS

BY BERTIL LÖFQUIST¹

SYNOPSIS

The problem relating to the magnitude of the horizontal ice pressure produced by a solid sheet of ice as a result of rapidly rising temperatures has not found a satisfactory solution. Investigations have yielded unreliable and somewhat contradictory results. This paper describes an investigation that was undertaken by the Swedish State Power Board. In the experiments, made with an arrangement installed in a freezing chamber, a pressure of 20 tons per m (13,400 lb per lin ft) was obtained with ice 60 cm (23.62 in.) thick. This result is somewhat unreliable, however, owing to the presence of certain additional effects during the experiment. From calculations made on the buckling of an ice sheet, a probable maximum ice pressure of from 30 tons per m to 40 tons per m (20,000 lb per lin ft to 27,000 lb per lin ft) is found. It would seem that an ice pressure of similar magnitude may also be set up under certain unfavorable local conditions in consequence of variations in the water level, with an ice sheet having a limited expanse of from 20 m to 40 m (65 ft to 130 ft). As a rule the ice pressure resulting from variations in the water level will be less, but it may occur in many places with appreciably greater frequency than ice pressure resulting from extreme temperature variations.

PRIOR INVESTIGATIONS

Numerous different opinions have been expressed concerning the magnitude of the horizontal pressure set up by a solid sheet of ice as a result of increased temperatures. Originally, it was believed that the ice pressure was limited by the compressive strength or elasticity of the ice, and in such cases—even under very favorable assumptions—very high working pressures were assumed. De-

NOTE.—Written comments are invited for publication; the last discussion should be submitted by June 1, 1953.

¹ Chf., Structural Research Div., State Power Board, Stockholm, Sweden.

spite the fact, however, that many dams that would be entirely incapable of withstanding pressures calculated in the foregoing manner were found to stand up well for long periods, it was recognized that this method of approach was not correct. It is now known that it is the plasticity of the ice that reduces the magnitude of the pressure considerably, and consequently lower values for the ice pressure were assumed subsequently. It has even been asserted that the plasticity of the ice is so great that the pressure at increased temperatures could be ignored.

In Sweden, when dimensioning dams and other structures in rivers and lakes, it is usual to assume a horizontal pressure from a solid ice sheet varying between 5 tons per m and 30 tons per m according to the geographical position and the judgment of the designer.

The first investigations of a more exhaustive nature relating to ice pressure from rapidly rising temperatures, in which allowance was made both for the course of the temperature and the actual deformation properties of the ice, were carried out in the year 1922 by Nils Royen.² As the result of these investigations a maximum ice pressure of 30 tons per m was found with an ice thickness of 1 m (40 in.).

The interesting and well-known experiments that were undertaken in 1932 by Ernest Brown and George C. Clarke,³ M. ASCE, represented a valuable contribution to knowledge on the deformation properties of ice. The experiments did not lead to a solution of the problem concerning the maximum ice pressure, however, since the relation between change of temperature and the stresses was only ascertained for an ice temperature with a linear rise. The course of events is more complicated in an ice sheet as the temperature curves are bent, and as the bends vary with the time and with the depth below the surface of the ice. The application of the test results, therefore, is accompanied by difficulties.

An attempt to compute the ice pressure on the basis of the Brown-Clarke experimental data was made by Edwin Rose⁴ and B. R. McGrath.⁵ These writers based their work partly on the Brown-Clarke curve for the relation between the rates of temperature rise and increase in pressure, and partly on the course of the temperature in the ice sheet, determined by a numeral method.

In this manner, ice pressures were obtained by a summation process, these values in general appearing reasonable. However, the method is not quite correct. An integration of the component forces will be mathematically permissible only if a linear relation exists between the stress and strain (principle of superposition). In the present case, this is true only with a linear temperature rise, according to the experiments. From the physical point of view it is not permissible, as a rule, to add to a component of force set up in the ice at a given point of time, in consequence of restrained temperature expansion,

² "Ice Pressure by Temperature Rise," by Nils Royen, *Homage Book in Honour of V. Hansen*, Swedish State Power Board, Stockholm, Sweden, 1922 (in Swedish).

³ "Ice Thrust in Connection with Hydro-Electric Plant Design," by Ernest Brown and George C. Clarke, *The Engineer Journal*, January, 1932.

⁴ "Thrust Exerted by Expanding Ice Sheet," by Edwin Rose, *Transactions, ASCE*, Vol. 112, 1947, p. 871.

⁵ Discussion by B. R. McGrath of "Thrust Exerted by Expanding Ice Sheet," by Edwin Rose, *ibid.*, p. 887.

another component of force set up at a later point of time. The first component has actually been reduced to some extent at the later point of time on account of the plasticity. The concept of the distribution of stresses in the ice sheet obtained by this method will therefore be improbable. Moreover, as demonstrated subsequently, the relation between the ice pressure and the thickness of the ice obtained by the method in question is also improbable, since it increases almost linearly with the ice thickness. Investigations described in this paper tend rather to show that the ice pressure already reaches its maximum value with an ice thickness of about half a meter, after which the pressure falls slightly with increasing thickness; or, in any case, it increases only to a relatively insignificant extent.

Computations of the ice pressure based on elementary experiments, with small sample blocks of ice, yield unreliable results, since the effect on the plasticity of the sample's size and the distribution of the stresses are difficult to determine. When it is desired to obtain reliable figures for the ice pressure, the best method for doing so consists of measuring the forces in question directly on an ice sheet in the field. Admittedly, it is scarcely possible to measure the maximum pressure directly, because it occurs only under exceptional conditions, but it should nevertheless be possible, after taking a large number of measurements in the field, to obtain a good starting point for determining the probable maximum pressure. With a combination of systematic laboratory experiments and field measurements it should become possible to solve the old problem of ice pressure by temperature rise in an entirely satisfactory manner. The ice pressure measurements made on natural sheets of ice begun by the Bureau of Reclamation⁶ (USBR), United States Department of the Interior, are therefore of great value in this respect.

ICE PRESSURE MEASUREMENTS UNDER LABORATORY CONDITIONS

In 1943 the writer attempted to solve the ice pressure problem with the help of an experimental arrangement in a freezing chamber. Although the experiment did not lead to an entirely satisfactory result, some observations were made during the course of the tests that are of interest. The underlying idea consisted of attempting to reproduce in a freezing chamber the conditions encountered in a sheet of ice in the field, and then measuring the course of the temperature and the stresses set up in the ice directly.

Experimental Arrangement.—The experimental arrangement is illustrated in Fig. 1 referring to the numbered points in Fig. 1(a): It consists essentially of a cylindrical concrete vessel (1) having an internal diameter of 50 cm (20 in.), filled with water, and thermally insulated with sawdust (11). The vessel is placed in a freezing chamber and, when the temperature is lowered, a sheet of ice is formed in the vessel in a manner similar to that occurring in nature. The heat transmission in the ice, when cooled and heated, takes place only in a vertical direction.

⁶ "Ice Pressure Measurements at Eleven Mile Canon Reservoir During January, 1949," Report No. SP-21, Structural Research Lab., Bureau of Reclamation, U. S. Dept. of the Interior, Washington, D. C., April, 1949.

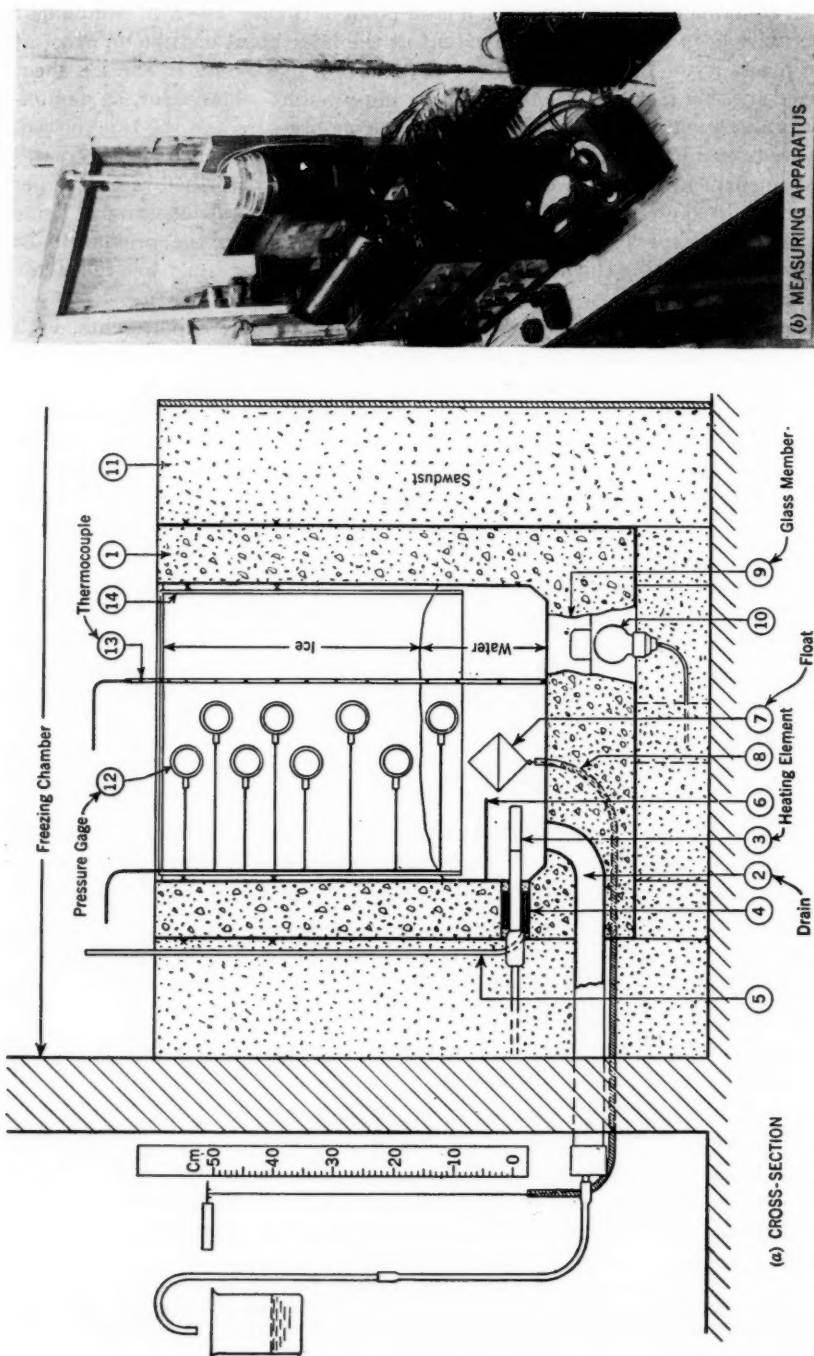


FIG. 1.—LABORATORY APPARATUS FOR MEASURING ICE PRESSURE

The stresses in the ice are measured by pressure gages (12) of a special type, and the temperature in the air, ice, water, and concrete is observed with the help of a number of thermo-elements (13).

The pressure gages (Fig. 2) consist in principle of two flat steel plates, electrically insulated from one another and from the outer, thicker pressure plates by thin sheets of mica. The electrical capacity of the device is sensitive to changes of pressure. Deformation in the direction of pressure is extremely small and may be neglected when taking measurements in ice. Since the pressure gage is constructed of steel (which has approximately the same coefficient of thermal expansion as the reinforced concrete in the experimental vessel), the relative expansion between the pressure gage and the ice, on changes of temperature, can be ignored.

The thickness of the ice is measured by a float (7). The float is held by a thin steel wire that runs in a tube (8) filled with mercury. Thus, the thickness of the ice can be read on a scale outside the freezing chamber.

In order to prevent freezing at the bottom and to regulate the thickness of the ice, an electric heating element (3) is placed at the bottom of the vessel. A protective plate (6) covering the heating element distributes the rising water

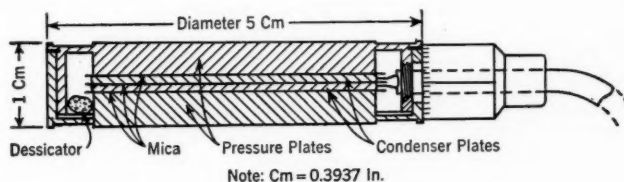


FIG. 2.—ICE PRESSURE GAGE

that has been heated. To prevent leakage, which might cause short circuits and burned insulation, the bushing at point 4, Fig 1(a), was packed with cement and an inside filling of wood tar. This wood tar filling was placed under a higher pressure than the water at the same level by means of a rising tube (5), thus insuring complete safety. The vessel is provided with bottom illumination (10) through a glass member (9) so that the formation of cracks in the ice can be seen clearly. Finally, a bottom drain (2) is fitted to carry off the water displaced during freezing.

When the ice sheet increases in thickness and the temperature falls, tensile stresses are set up in the ice, giving rise to cracks. In the first two experiments, it was found that the cracks were formed when the temperature at the surface of the ice had fallen to about -12°C (10°F). The fine cracks did not spread down to the underside of the ice and could not be filled with water and freeze again, as in the case of open cracks in a natural ice sheet of wide expanse. No great ice pressure could occur, therefore, during the subsequent temperature rise. In the two first tests the pressure amounted to approximately 5 tons per m with an ice thickness of 50 cm. This value thus corresponds to the ice pressure in ice sheets of small extent, such as those encountered in small reservoirs where continuous cracks of sufficient width do not occur.

In order to produce the same conditions for ice pressure as those existing in a large ice sheet, double cylindrical plates (14) were arranged in the concrete vessel and connected at the bottom and at the sides. In this manner an air-filled gap (a cylindrical contraction joint) was obtained so that the ice could be cooled to the desired temperature without cracking. Before raising the temperature, the gap was carefully filled with water that froze to ice. However, in this operation, it was not possible to eliminate crack formation in the ice sheet entirely, which probably exercised a reducing action on the ice pressure set up subsequently.

RESULTS OF THE EXPERIMENTS

Figs. 3 to 6 show the results of a typical test that gave a maximum pressure of 20 tons per m (13,400 lb per lin ft) when the temperature of the air was

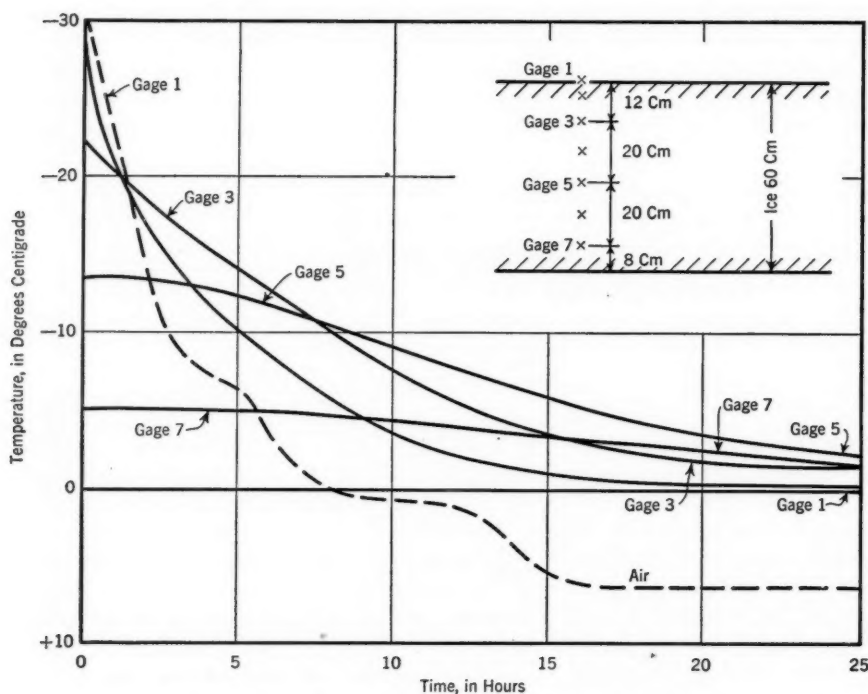


FIG. 3.—TIME RATE OF TEMPERATURE RISE, TEST NO. 4

raised from -30°C to $+6^{\circ}\text{C}$ in 17 hr. Two further tests, under similar conditions, also gave a maximum pressure of about 20 tons per m. In consequence of the thermal expansion of the concrete vessel, the conditions did not correspond to perfect restraint. The pressure in the case of perfect restraint can be estimated to be about 25% higher.

Two effects made their appearance during the experiments, however, which exercised a disturbing action on the results in different directions. On the one hand, as stated, a number of cracks were formed in the ice when filling the air

gap, and these cracks probably exercised a reducing effect on the ice pressure. The irregularities, visible in the curves for pressure in Fig. 5, may be ascribed mainly to the effect of these cracks. On the other hand, the expansion of the ice in a vertical direction at the walls of the vessel is prevented to a certain

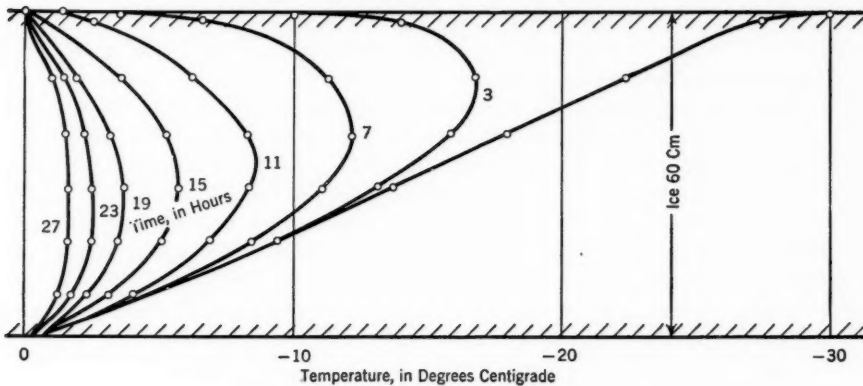


FIG. 4.—TEMPERATURE DISTRIBUTION, TEST NO. 4

extent by adhesion. The additional vertical stresses thus set up produce compressive stresses in a horizontal direction in the central depth of the ice sheet and tensile stresses at the surface. The action of the compressive stresses

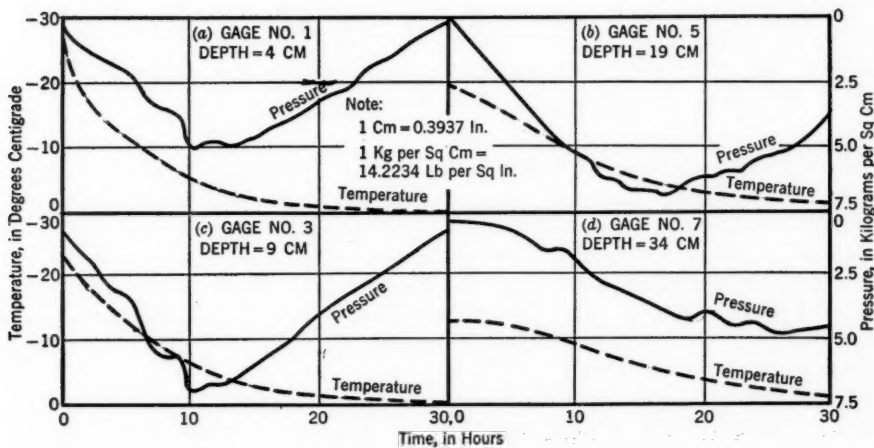


FIG. 5.—TIME VARIATION OF PRESSURE AND TEMPERATURE FOR SAME GAGE, TEST NO. 4

nevertheless preponderates, so that the result will be a certain increase in the total ice pressure. Had it been possible to eliminate the effects in question, the "pear" shape appearance of the pressure distribution in Fig. 6 would probably have been less pronounced.

In principle, however, the curves should not present a changed appearance since, if the temperature at the surface of the ice is 0°C , or close to it, when the total maximum pressure is reached, the compressive stresses in the surface layer itself must be relatively small. It was observed that the surface of the ice, which was smooth at the outset, had become buckled at the conclusion of the experiment as a result of the compressive stresses, and presented a rough appearance. This phenomenon is probably one of the reasons for the relatively small pressure in the surface layer.

In Fig. 7 the results of two of the most successful experiments have been drawn on a diagram of the type produced by Messrs. Brown and Clarke. The difference between the curves obtained by varying means is considerable, and illustrates fairly clearly the difficulty of obtaining a correct grasp of the ice pressure problem. The difference, of course, results in part from the fact that the upper curve is based on experiments in which the conditions of stress are mainly uni-dimensional whereas the lower curve is based on chiefly two-dimensional stresses. Moreover, an appreciable difference may exist between

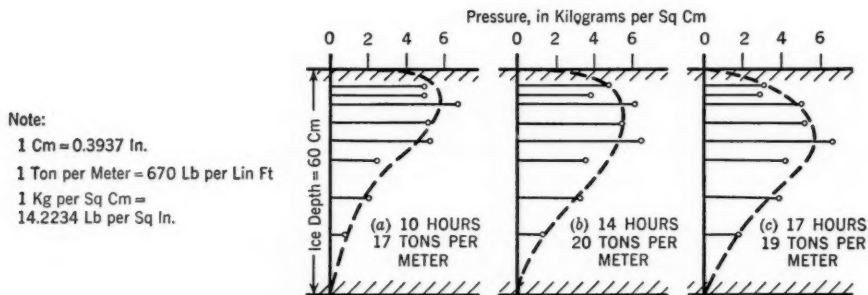


FIG. 6.—PRESSURE DISTRIBUTION IN A CROSS SECTION OF ICE

different kinds of ice—a circumstance concerning which current knowledge is still very imperfect. In the experiments described, tap water was used for producing the ice. The water was heated to boiling point to reduce the air content. On applying pressure parallel to the surface of the ice a compression strength at 0°C of about 50 kg per sq cm was obtained with sawed out ice cubes. In ice investigations of this kind, the salt content of the water (ice) should always be stated exactly, as the plastic properties appear to vary considerably with the salt content, even when the latter is low.

Although the results of the experiments are unreliable as regards the absolute magnitude of the ice pressure, they nevertheless afford the possibility of throwing some light on another interesting question—namely, the relation between the ice pressure and ice thickness. The general opinion seems to be that ice pressure of the kind concerned increases appreciably with the thickness of the ice even in the case of thick ice. Closer investigation tends to show that the ice pressure reaches its maximum at a thickness of about half a meter, and thereafter it falls slightly, or in any case only increases to an insignificant extent. The reason for this behavior is that the rate of temperature rise in ice is rapidly

reduced as the thickness of the ice increases. This effect compensates for the action of the increased thickness.

As will be seen from Fig. 7, the ice pressure increases with the rate of temperature rise in accordance with a curve that only appears to bend slightly within the actual range. If a certain course of the temperature in the air is assumed, such as a change from -30°C to 0°C in 10 hr, after which it remains constant at 0°C , it is possible to calculate the course of the ice's mean temperature mathematically. On the basis of the temperature variations in the ice the diffusivity constant of the ice can be computed by means of difference equations at 0.0048 m per hr, which agrees fairly closely with the particulars given in the literature on the subject. Experiments showed that the maximum pressure was produced when the mean temperature reached about -4°C (see Figs. 3 to 6). On this assumption, and on the basis of the temperature's mean rate of

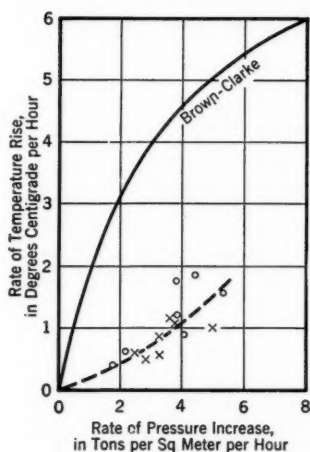


FIG. 7.—RELATION BETWEEN TEMPERATURE RISE AND PRESSURE RISE, TESTS 3 AND 4

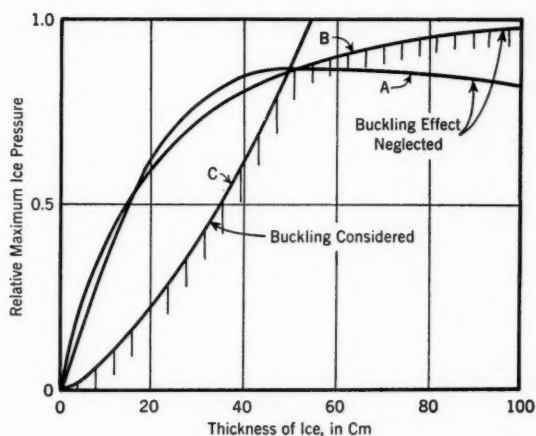


FIG. 8.—PROBABLE RELATION BETWEEN MAXIMUM ICE PRESSURE AND ICE THICKNESS

rise, it is possible to calculate approximately the relative maximum pressure with different ice thicknesses. A maximum is found with an ice thickness of about 0.5 m (Fig. 8, curve A). It is nevertheless possible that the maximum pressure may occur at a somewhat lower temperature than -4°C , with a considerable thickness of ice, since the temperature will then follow a slower course. When this fact is taken into consideration, the maximum point will be displaced to a greater thickness of ice, but the increase for thicknesses exceeding 0.5 m will not be appreciable (Fig. 8, curve B).

The foregoing reasoning is based solely on the properties of the ice itself. Under field conditions in most cases the heating of the ice begins in the morning after a cold night and proceeds during the entire day. With small thicknesses of ice the maximum pressure may then be obtained before the temperature falls again in the evening, whereas this is not the case with greater thicknesses of ice, which require a time of 20 hr or more to attain the maximum pressure. This

fact also argues in favor of the probability of an ice pressure maximum in nature with an ice thickness of about 0.5 m.

BUCKLING OF AN ICE SHEET

When the horizontal pressure in a sheet of ice attains a certain magnitude the ice will buckle. This phenomenon may frequently be observed with a thickness of ice as great as from 20 cm to 30 cm, whereas it appears to occur very rarely with a thickness of 50 cm. This fact indicates a method of estimating the ice pressure by calculation. The difficulty here, as in the case of other ice pressure problems, is to find a correct value for the modulus of elasticity of the ice with due regard to the plasticity. As will be seen, however, an erroneous assumption will not have the same far-reaching effect as when determining the ice pressure directly from the thermal expansion.

The buckling of an ice sheet can be computed by the theories for beams or slabs resting on an elastic bed. In an ice sheet of wide extent the buckling load H will be

$$H = \sqrt{\frac{k d^3 E m^2}{3(m^2 - 1)}} \dots \dots \dots (1)$$

in which k is the modulus of reaction (the uplift in water); d is the thickness of the ice; E is the modulus of elasticity; and m is the Poisson ratio.

To account for the plastic character of the ice, E is replaced by a "modulus of deformation," F which includes both the elastic and the plastic deformation as well as the effect of lateral restraint. Eq. 1 can then be written:

$$H = \sqrt{\frac{k d^3 F}{3}} \dots \dots \dots (2)$$

When investigating the lifting force of an ice sheet,⁷ the following expression for the modulus of deformation was found to agree satisfactorily with measurements of the deflection of a natural sheet of ice:

$$\frac{1}{F} = \frac{1}{E} + \frac{C \sqrt[3]{h}}{t + 1} \dots \dots \dots (3)$$

in which C is a constant equal to 8×10^{-5} when calculating in tons, meters, degrees Centigrade, and hours; h is the time in hours; and t is the ice temperature in degrees Centigrade with reversed sign.

When using Eq. 3 it is necessary to know the ice temperature and the time for the buckling process. The value of $1/E$ can here be neglected in relation to $1/F$. The maximum pressure occurred when the mean temperature of the ice was about -4°C . On deflection, however, the upper and lower extreme "fibers" of the ice sheet will be most active, so in this case the effective mean temperature can be assumed at about -2.5°C . The time for the buckling process can be estimated on the basis of the curves in Fig. 5 at 2 hr to 4 hr at least, if visible buckling is to be produced. Thus, for an ice thickness of 0.5 m,

⁷ "Lifting Force and Bearing Capacity of an Ice Sheet," by Bertil Löfquist, *Technical Translation, TT-164*, National Research Council of Canada, Ottawa, Ont., Canada, 1951 (From *Teknisktidskrift*, No. 25, Stockholm, Sweden, 1944).

$t = 2.5$ and $h = 3$, according to Eq. 3 it is found that $F = 30,000$ tons per sq m, and according to Eq. 2, $H = 35$ tons per m. In general, if the assumptions are varied within the limits of probability, buckling forces between 30 tons per m and 40 tons per m are obtained.

In Fig. 8, curve C, shows the manner in which the buckling load varies with the ice thickness in accordance with the foregoing assumption. Thus, it will be seen that the buckling load determines the magnitude of the ice pressure with lesser thicknesses than about 0.5 m and that the reduction in the ice pressure thus produced is appreciable. The relation between curve C and curves A and B in Fig. 8 is based on the assumption that an ice sheet thicker than 0.5 m will not buckle.

These calculations are open to discussion in many respects, of course, but they should suffice to show that it is possible in this manner to determine the maximum ice pressure within fairly narrow limits.

ICE PRESSURE CAUSED BY VARIATIONS OF WATER LEVEL

Buckling results not only from temperature rises but is also far more frequently caused by variations in the water level. When the water level falls, the ice sheet is subjected to tensile stresses if it is frozen to the shore. Thus, wide open cracks may be produced in the ice in a moment. The cracks may freeze again and a horizontal pressure is set up in the ice sheet when the water level rises.

A similar effect may also occur because of the fact that on changes of water level, the ice is repeatedly broken by bending forces produced at the shore or against a dam structure, and the cracks fill with water and freeze again. If open channels are formed in the ice (as is frequently the case in rivers and waterways), the ice will have a tendency to move out from the shore and will thereby exercise a horizontal force on structures that obstruct its movement. Many cases of trouble caused by ice pressure of this kind have been observed.

The magnitude of the ice pressure with variation of water level is largely dependent on local conditions and it is consequently difficult to obtain any general value. For ice sheets of wide extent in a plane, the pressure in question seemed to be comparatively moderate, but in smaller ice sheets it appears that the forces of pressure may be of the same order of magnitude as in the case of extreme temperature variations. In particular cases it is possible to make approximate calculations for the pressure with the help of Eq. 3 for the modulus of deformation and with the help of formulas for the buckling load, and assumptions concerning the form of the ice sheet. It would seem that the most unfavorable conditions prevail, as a rule, with a span across the ice sheet of from 20 m to 40 m, when the ice sheet may form a complete arch between supports.

Perhaps ice pressure of the kind in question will not be so great in many places as the maximum ice pressure resulting from temperature variations. It will probably occur far more frequently, however, since it does not require the coincidence of so many unfavorable conditions as in the case of ice pressure caused by temperature variations. In order to obtain wider knowledge on this

subject, further measurements must be made in the field, mainly leveling ice sheets with different spans at varying water levels.

When the water level rises, the ice sheet can also exert lifting forces that are of special significance for smaller hydraulic constructions.⁷

ACKNOWLEDGMENT

The pressure gage in Fig. 2 was designed by C. H. Johannssen⁸ and J. O. Linde at the Royal Institute of Technology in Stockholm, Sweden.

⁸ "Neue Kondensatordruckkraftmesser," by C. H. Johannssen, *Annalen der physik*, Vol. 27, 1936, p. 742.

CURRENT PAPERS AND DISCUSSIONS

Proceedings- Separate Number	Date Available	Title and Author	Discus- sion closes
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